

Theoretical Overview of e+p physics at an EIC

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**XIX International Workshop on Deep-Inelastic Scattering and Related
Subjects (DIS 2011), April 11-15, 2011**

Newport News Marriott at City Center, Newport News, VA USA

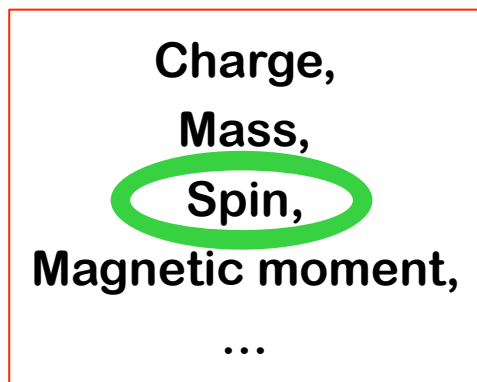
Outline of my talk

- ❑ Question(s)
- ❑ Challenges for theorists
- ❑ Why EIC – EIC advantages?
- ❑ Physics opportunities
- ❑ Summary

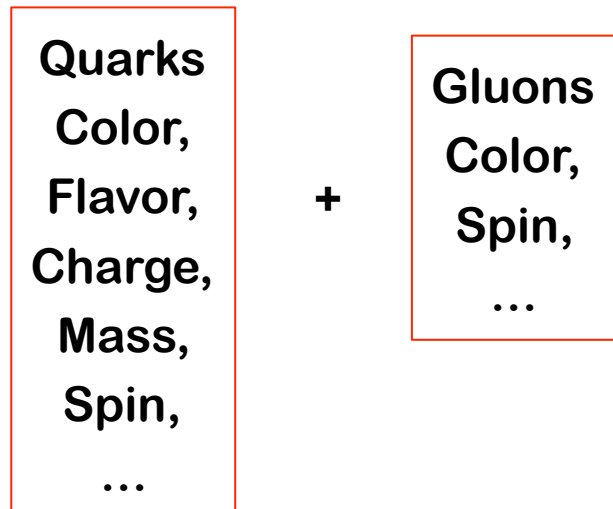
Challenges of strong interaction

□ Hadron properties in terms of dynamics of quarks and gluons:

Hadron properties



QCD



□ Lattice QCD:

Could calculate all hadron properties in principle!

Has done an excellent job in reproducing the hadron mass spectrum

□ But,

It does not reveal the space-time distribution of partons inside a hadron, details of interactions, reasons of confinement, ...

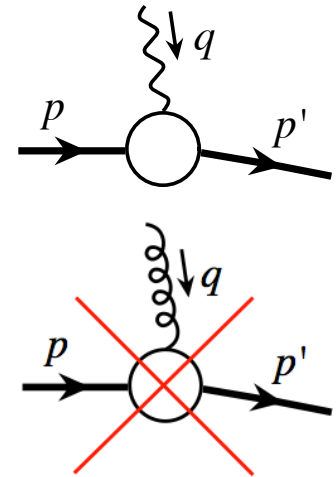
The “big” question(s)

- How color is distributed inside a hadron?
(possible clue for color confinement, ...)

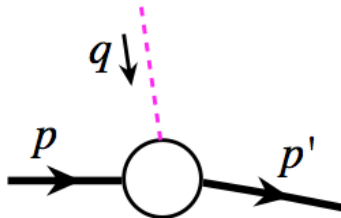
✧ Electric form factor \longrightarrow charge distribution

But, no color form factor!

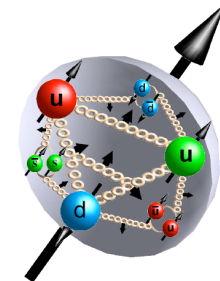
Hadron is color singlet and gluon carries color



- How partons are distributed inside a hadron?
(hadron's partonic structure, ...)



Need an effective strong interacting, but, color singlet current to keep the proton intact



OR use an inclusive process with a “localized” probe

Hadron's partonic structure

□ Ideal solution:

✧ Measure or calculate matrix elements:

$$\langle p, s | \mathcal{O}(\bar{\psi}_q, \psi_q, A^\mu) | p, s \rangle$$

with ALL possible combinations of parton fields

✧ Two parton correlations – parton densities:

$$\langle p, s | \bar{\psi}_q(0) \Gamma \psi_q(y) | p, s \rangle \quad \langle p, s | F^{+\alpha}(0) F^{+\beta}(y) | p, s \rangle$$

✧ Three parton correlations – measure of color forces:

$$\langle p, s | \bar{\psi}_q(0) \Gamma [\epsilon_{\perp}^{sT\sigma} F_{\sigma}^{+}(y')] \psi_q(y) | p, s \rangle$$

$$\langle p, s | \bar{\psi}_q(0) \Gamma [s_T^{\sigma} F_{\sigma}^{+}(y')] \psi_q(y) | p, s \rangle, \dots$$

✧ Multi-parton correlations – coherence of parton fields:

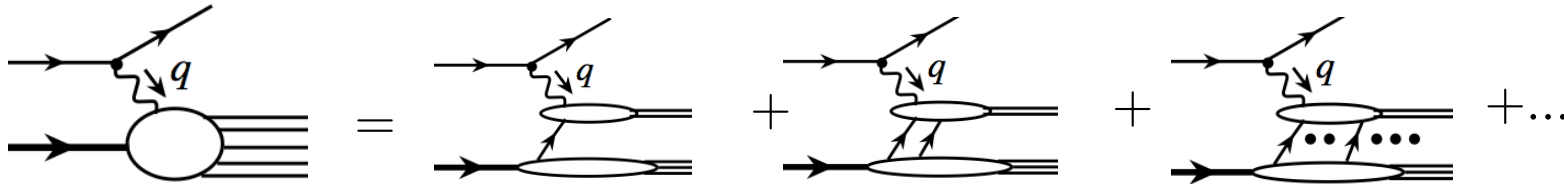
$$\langle p, s | \bar{\psi}_q(0) \Gamma [F_{\alpha}^{+}(y_1) F_{\beta}^{+}(y_2)] \psi_q(y) | p, s \rangle, \dots$$

□ Problem:

None of these matrix elements is a direct observable!
– color confinement

Challenges

□ Hadronic cross sections:



✧ Every parton can participate the hard collision!

✧ Hadronic cross section depends on matrix elements of all fields

□ Approximation – large momentum transfer: $Q \gg 1/\text{fm}$

$$\sigma(Q) = \sigma^{\text{LP}}(Q) + \frac{Q_s}{Q} \sigma^{\text{NLP}}(Q) + \frac{Q_s^2}{Q^2} \sigma^{\text{NNLP}}(Q) + \dots \approx \sigma^{\text{LP}}(Q)$$

□ Factorization - approximation:

$$\sigma(Q) \approx \sigma^{\text{LP}}(Q) \propto \hat{\sigma}(Q) \otimes \langle p, s | \tilde{\phi}^\dagger(k) \tilde{\phi}(k) | p, s \rangle + \dots$$

□ Challenges for theorists:

Hadron's partonic structure!

To identify measurable and factorizable physical quantities
– carry rich information on hadron's partonic structure

Why EIC?

□ Probes for hadron's partonic structure need:

✧ A large momentum transfer: $Q \gg 1/\text{fm}$

Localized probe, suppress contribution of complicate matrix elements

✧ A small momentum scale: $Q_2 \sim 1/\text{fm}$

Sensitive to parton's motion inside a hadron

✧ QCD factorization can be applied!

$$\sigma(Q) \approx \sigma^{\text{LP}}(Q) \propto \hat{\sigma}(Q) \otimes \langle p, s | \tilde{\phi}^\dagger(k) \tilde{\phi}(k) | p, s \rangle + \dots$$

Calibrated local probe!

Hadron's partonic structure!

✧ Polarization – probe different parton operators/structure:

$$\langle p, s | \mathcal{O}(\psi_q, A^\mu) | p, s \rangle - \langle p, -s | \mathcal{O}(\psi_q, A^\mu) | p, -s \rangle$$

□ EIC has advantages on all these requirements!

Some EIC e+p opportunities

Still interesting beyond 2020

- ❑ Inclusive DIS – Spin, F_L , ...
- ❑ SIDIS – TMDs, spin-orbital correlations, ...
- ❑ GPDs – parton spatial distributions
- ❑ ...




(A personal selection of limited topics in a limited time)

Many excellent talks in this conferences!

EIC webpages: <http://web.mit.edu/eicc/index.html>
<http://www.int.washington.edu/PROGRAMS/10-3/>

...

Golden PDF measurements

Science Deliverable	Basic Measurement	Uniqueness Feasibility Relevance	Requirements
spin structure at small x contribution of Δg , $\Delta \Sigma$ to spin sum rule	inclusive DIS	✓ 	need to reach $x=10^{-4}$ large x, Q^2 coverage about 10fb^{-1}
full flavor separation in large x, Q^2 range strangeness, $s(x)-\bar{s}(x)$ polarized sea	semi-inclusive DIS	✓ 	very similar to DIS excellent particle ID improved FFs (Belle, LHC, ...)
electroweak probes of proton structure flavor separation electroweak parameters	inclusive DIS at high Q^2	✓  some unp. results from HERA	20x250 to 30x325 positron beam ? polarized ^3He beam ?

Stratmann's talk to EICAC review

The “money” plot – inclusive DIS

□ Precision of $\Delta g(x, Q^2)$:

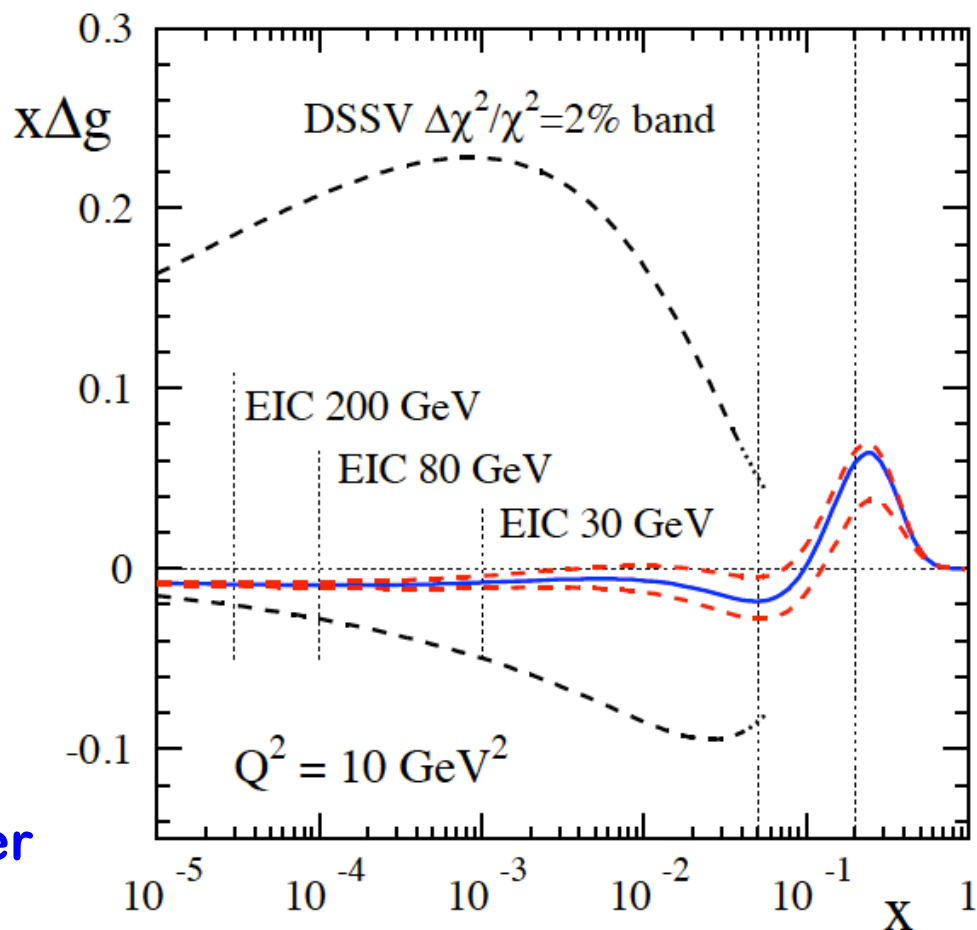
$$\frac{dg_1}{d \ln Q^2} \propto \Delta g(x, Q^2)$$

Expectation:

$$\int_0^1 dx \Delta g(x, Q^2) \text{ to 10\% level?}$$

□ Questions for theorists:

- ✧ Physics behind the node?
- ✧ Factorization at small- x ?
- ✧ Dominance of leading power when it is so small?
- ✧ ...




See stratmann's talk

$F_L(x, Q^2)$ – Inclusive DIS

□ Unfinished business of HERA:

Test of pQCD expansion
(NNLO – three loops)

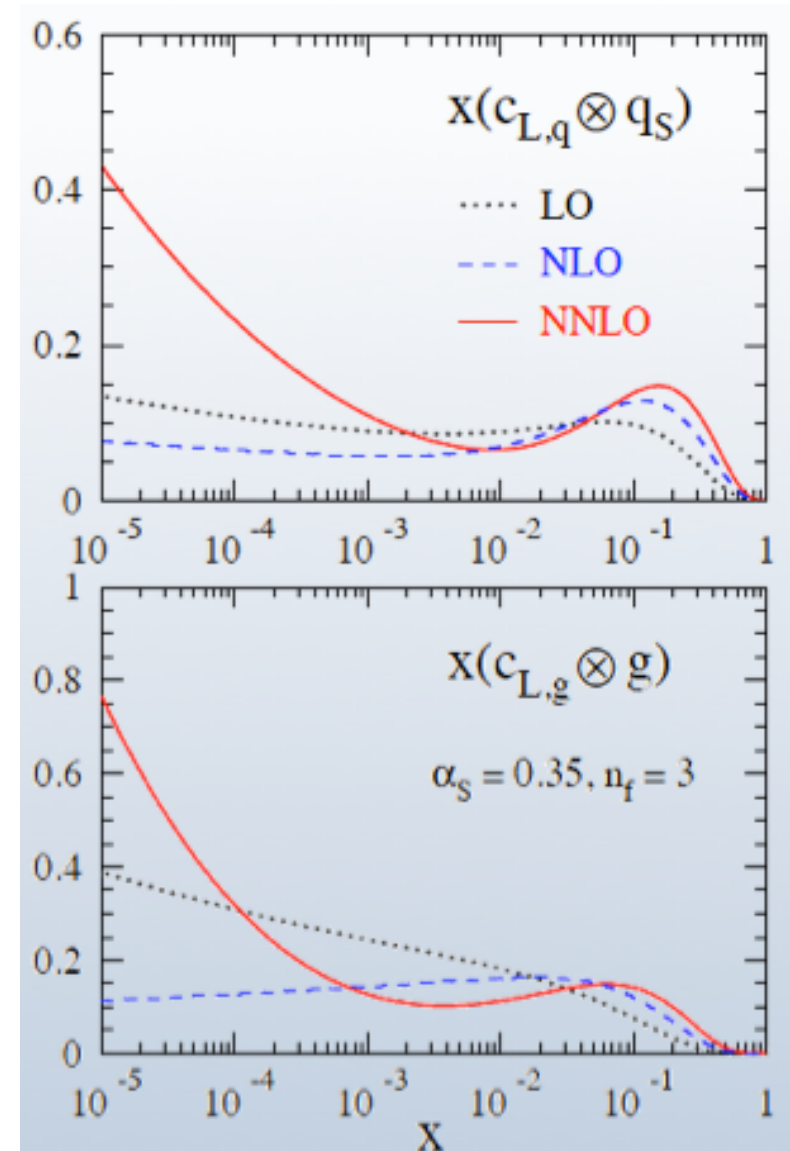
No small-x growth until NNLO

$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{16}{3} F_2(z) + 8 \sum_q e_q^2 \left(1 - \frac{x}{z}\right) z g(z) \right]$$


Direct measurement of gluon

NO scheme to eliminate
The gluon contribution to F_L
(DIS scheme: no gluon for F_2)

See stratmann's talk



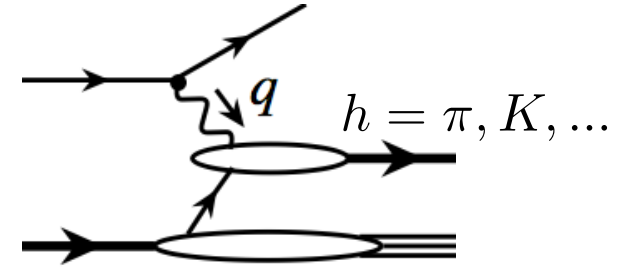
Quark flavor separation – SIDIS

- Integrate over final-state hadron's transverse momentum:

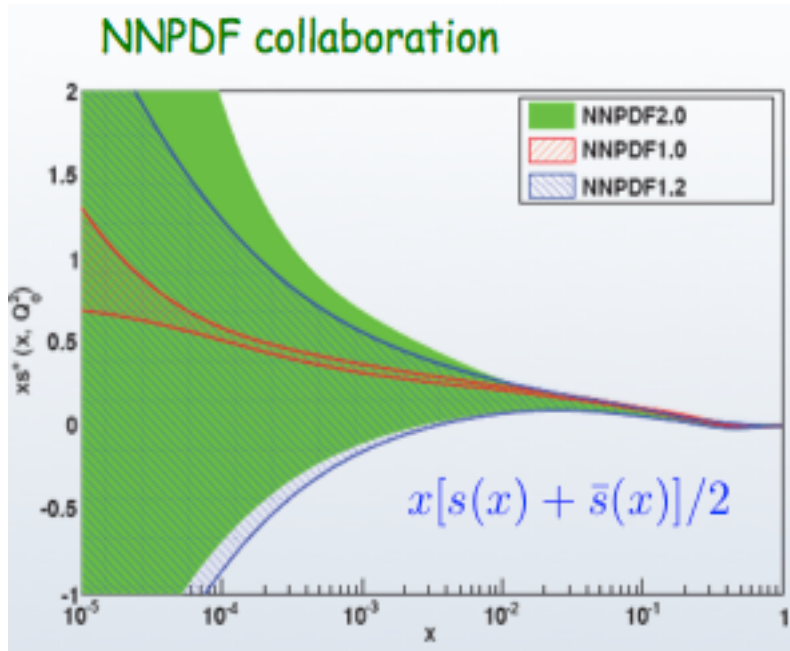
One hard scale – collinear factorization

$$h = \pi, K, \dots$$

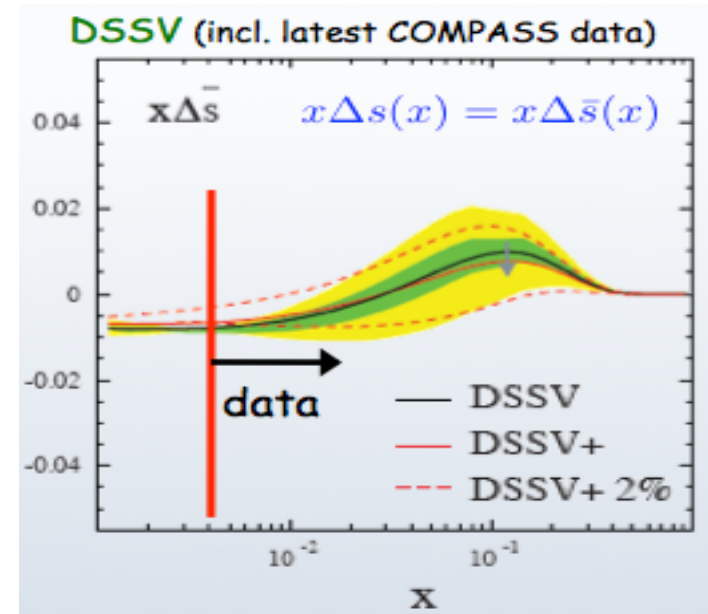
Separation of parton flavors



- Strangeness distributions:



NuTeV anomaly on $\sin^2 \theta_w$

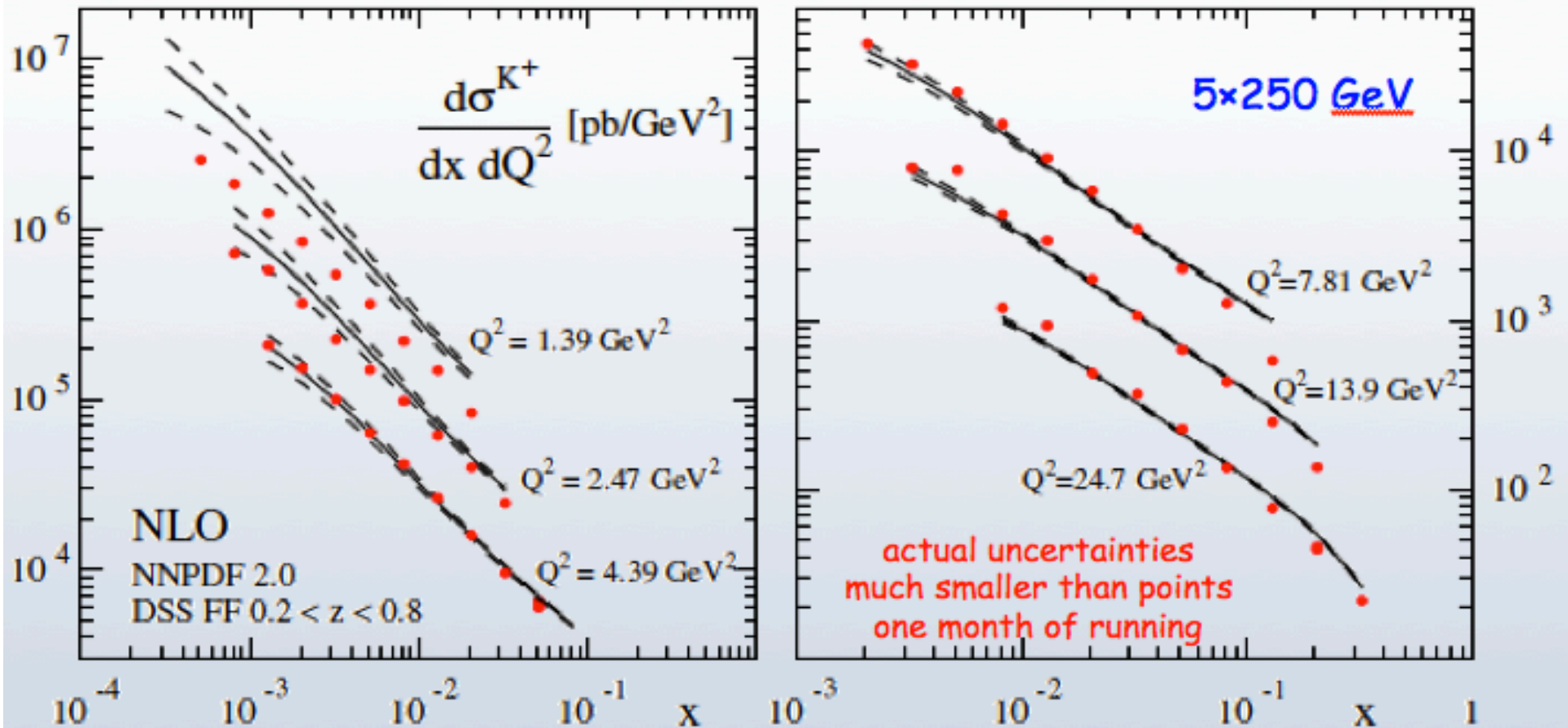


Tension with the 1st moment

EIC for charged kaons

compute K^+ yields at NLO with 100 NNPDF replicas
 z integrated to minimize FF uncertainties (work in progress)

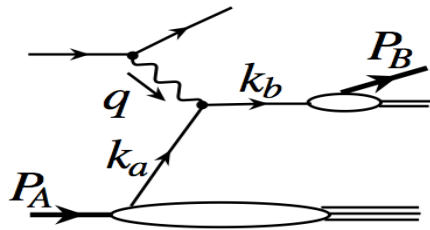
Aschenauer
Stratmann



PYTHIA agrees very well (despite *very* different hadronization model)

--> confidence that we can use MC to estimate yields & generate toy data

TMD factorization – SIDIS

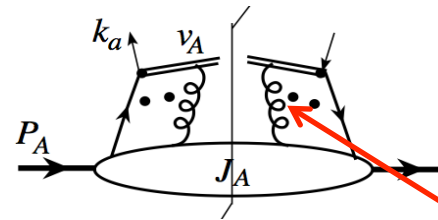


$$\sigma_0 \phi(x, \mu) \otimes D(z, \mu) \delta^2(p_{BT})$$

$$\sigma_0 \tilde{\phi}(x, k_{aT}) \otimes \tilde{D}(z, k_{bT}) \delta^2(p_{BT} - k_{aT} - k_{bT})$$

□ TMD parton distribution:

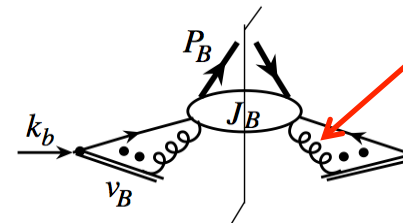
$$\tilde{\phi}_{f/A}^{(0)}(x, k_{aT}) = \text{Tr}_{\text{color}} \text{Tr}_{\text{Direc}} \frac{\gamma^+}{2} \int \frac{dk_a^-}{2\pi}$$



Gauge links

□ TMD fragmentation function:

$$\tilde{D}_{f \rightarrow B}^{(0)}(z, k_{bT}) = \frac{\text{Tr}_{\text{color}}}{N_c} \frac{\text{Tr}_{\text{Direc}}}{4} \frac{\gamma^+}{z} \int \frac{dk_b^-}{2\pi}$$



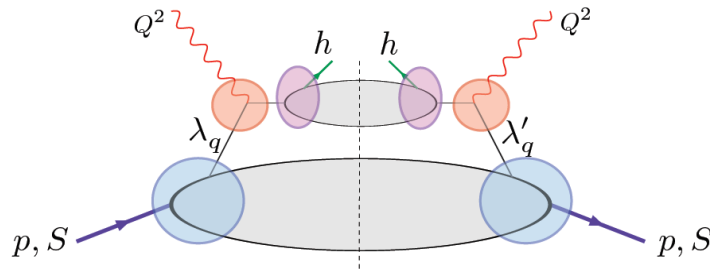
Phase for SSA

□ TMDs are more fundamental if we can measure them:

Carry more information on hadron's partonic structure

EIC is ideal for studying TMDs

□ SIDIS has the natural kinematics for TMD factorization:



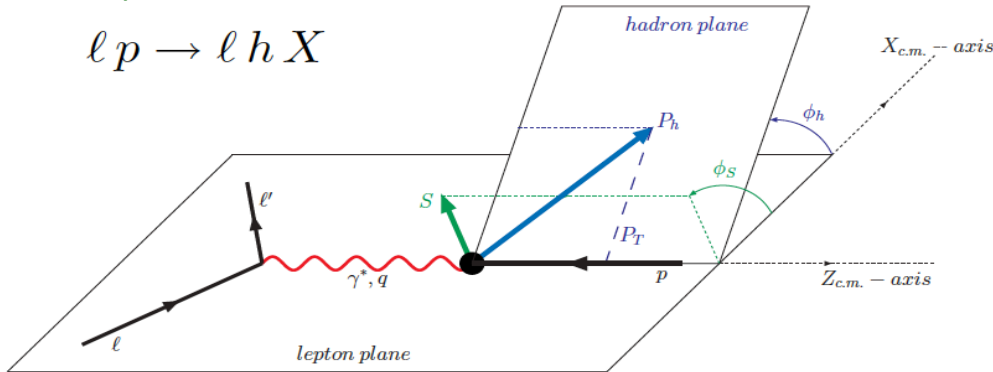
$$\ell(s_e) + p(s_p) \rightarrow \ell + h(s_h) + X$$

Natural event structure:

high Q and low p_T jet (or hadron)

□ Separation of various TMD contribution by angular projection:

$$\ell p \rightarrow \ell h X$$



Lepton plane vs. hadron plane

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S)$$

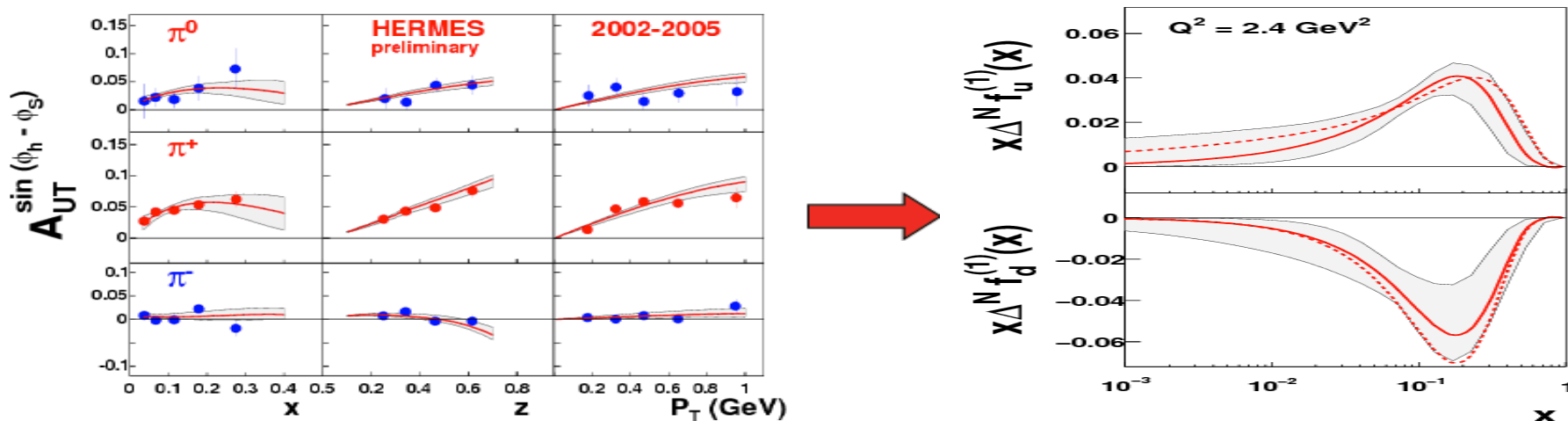
$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^\perp$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp$$

Our current knowledge on TMDs

□ Sivers function from SIDIS:



EIC can do much better job in extracting TMDs

□ Questions for theorists:

- ✧ Q^2 -dependence of TMDs in k_T -space?
- ✧ QCD resummation in b -space (CSS-type approach) for TMDs?
- ✧ NLO hard parts in k_T -space or b -space approach?
- ✧ ...

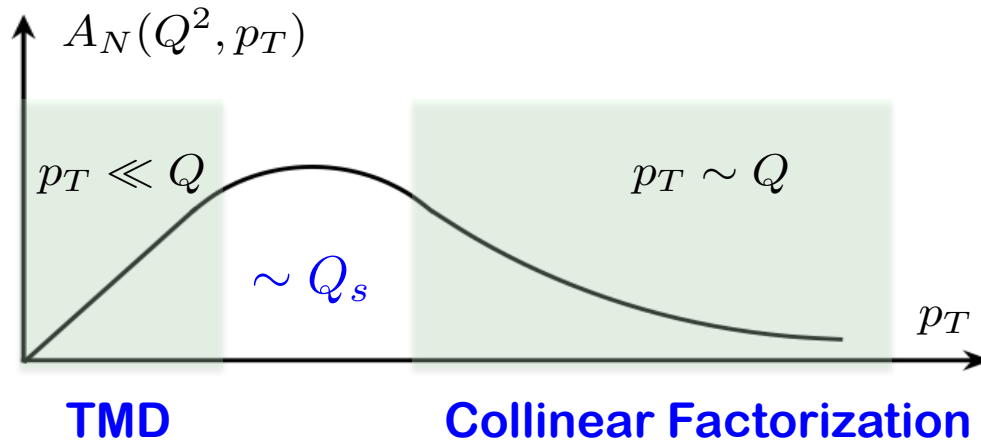
□ NO TMD factorization for hadron production in p+p collisions

Collins and Qiu, 2007, Vogelsang and Yuan, 2007, Mulders and Rogers, 2010, ...

From low p_T to high p_T

□ TMD factorization to collinear factorization:

Ji, Qiu, Vogelsang, Yuan,
Koike, Vogelsang, Yuan



Two factorization are
consistent in the overlap
region where

$$\Lambda_{\text{QCD}} \ll p_T \ll Q$$

□ Collinear factorization:

Efremov, Teryaev, 82; Qiu, Sterman, 91, etc.

$$\sigma(Q, \vec{s}) \propto \left| \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \\ \text{Diagram 3} \\ \vdots \end{array} \right|^2 = \sigma^{\text{LP}}(Q, \vec{s}) + \frac{Q_s}{Q} \sigma^{\text{NLP}}(Q, \vec{s}) + \dots$$

The diagrams show various Feynman-like diagrams for the cross-section $\sigma(Q, \vec{s})$. The first diagram is labeled p, \vec{s} and k . The second diagram is labeled $t \sim 1/Q$.

$$\Delta\sigma(s_T) \propto T^{(3)}(x, x) \otimes \hat{\sigma}_T \otimes D(z) + \delta q(x) \otimes \hat{\sigma}_D \otimes D^{(3)}(z, z) + \dots$$

$$T^{(3)}(x, x) \propto \text{Diagram}$$

The diagram shows a horizontal line with two vertices. The left vertex has an incoming line and a loop. The right vertex has an outgoing line and a loop. A vertical line connects the two vertices.

Qiu, Sterman, 1991, ...

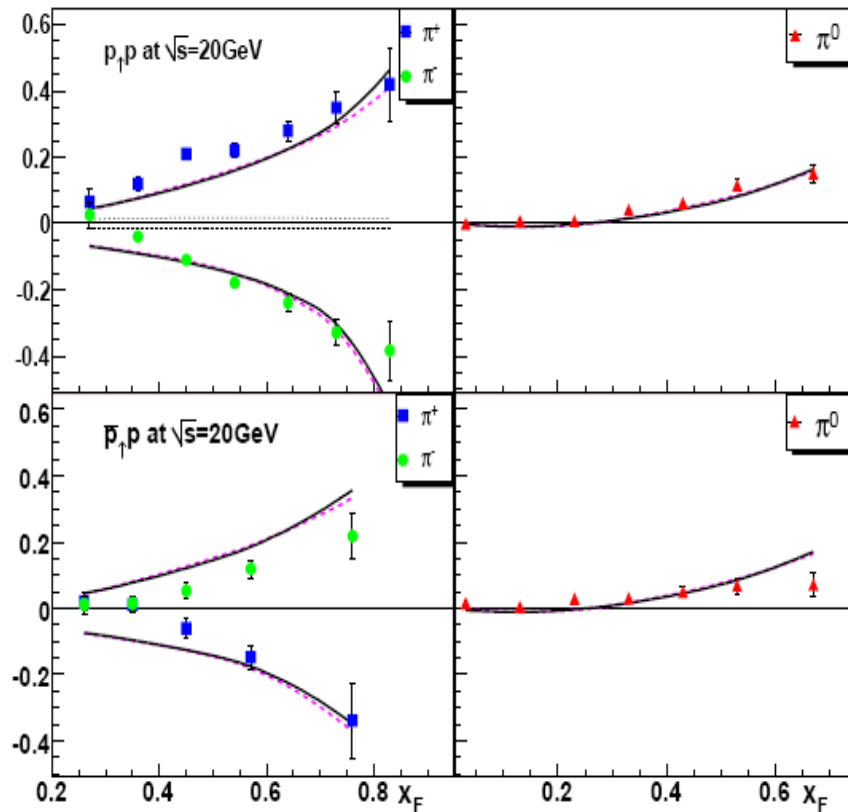
$$D^{(3)}(z, z) \propto \text{Diagram}$$

The diagram shows a horizontal line with two vertices. The left vertex has an incoming line and a loop. The right vertex has an outgoing line and a loop. A vertical line connects the two vertices.

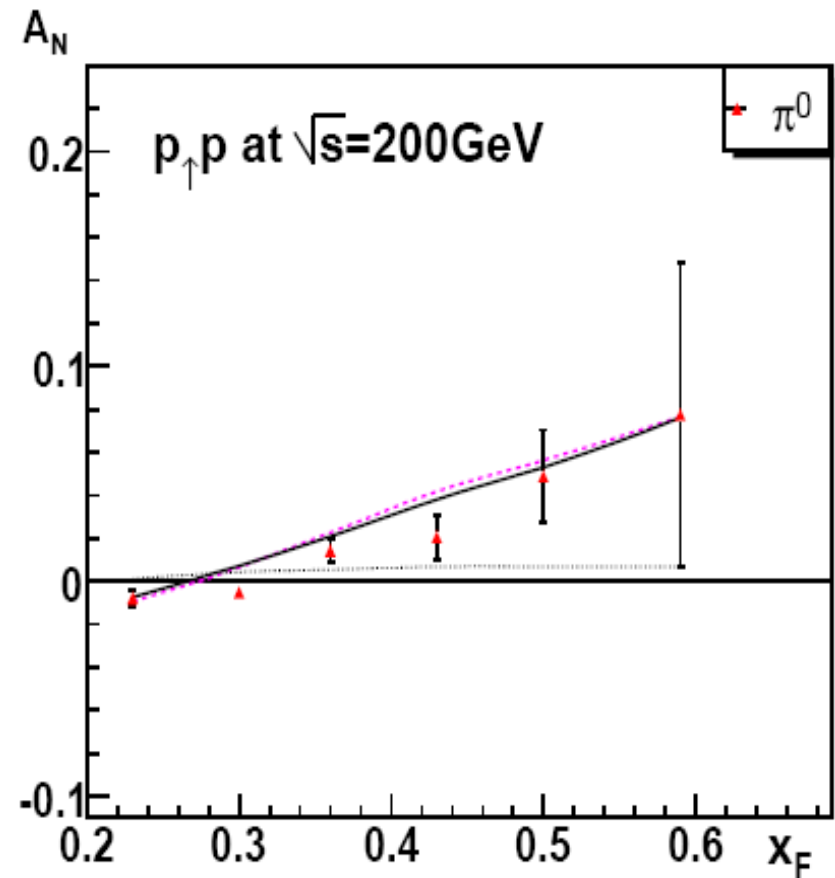
Kang, Yuan, Zhou, 2010

A_N from LO quark-gluon correlation

(FermiLab E704)



(RHIC STAR)



Kouvaris, Qiu, Vogelsang, Yuan, 2006

Nonvanish twist-3 function \longrightarrow Nonvanish transverse motion

Global QCD analysis for A_N

□ Universality of correlation functions:

$$\langle P, s | \bar{\psi}(0) \gamma^+ \psi(y^-) | P, s \rangle \quad \longrightarrow \quad \langle P, s | \bar{\psi}(0) \gamma^+ \left[\epsilon_{\perp}^{\alpha\beta} s_{T\alpha} \int dy_2^- F_{\beta}^+(y_2^-) \right] \psi(y^-) | P, s \rangle$$
$$\langle P, s | \bar{\psi}(0) \gamma^+ \gamma_5 \psi(y^-) | P, s \rangle \quad \longrightarrow \quad \langle P, s | \bar{\psi}(0) \gamma^+ \left[i g_{\perp}^{\alpha\beta} s_{T\alpha} \int dy_2^- F_{\beta}^+(y_2^-) \right] \psi(y^-) | P, s \rangle$$

Same replacement for the gluons

Kang, Qiu, 2009

□ Q^2 -dependence or evolution of correction functions:

Leading order evolution kernels for all channels have been derived!

Kang, Qiu, 2009

Yuan, Zhou, 2009

Braun et al, 2009

□ Questions/Tasks for theorists:

✧ NLO partonic contributions to SSAs

Vogelsang, Yuan, 2009

✧ How good is the factorization?

✧ Connection to the TMD approach – sign “mismatch”?

✧ ...

□ A completely new domain to test QCD!

From parton's transverse motion to direct QCD quantum interference

A sign “mismatch”

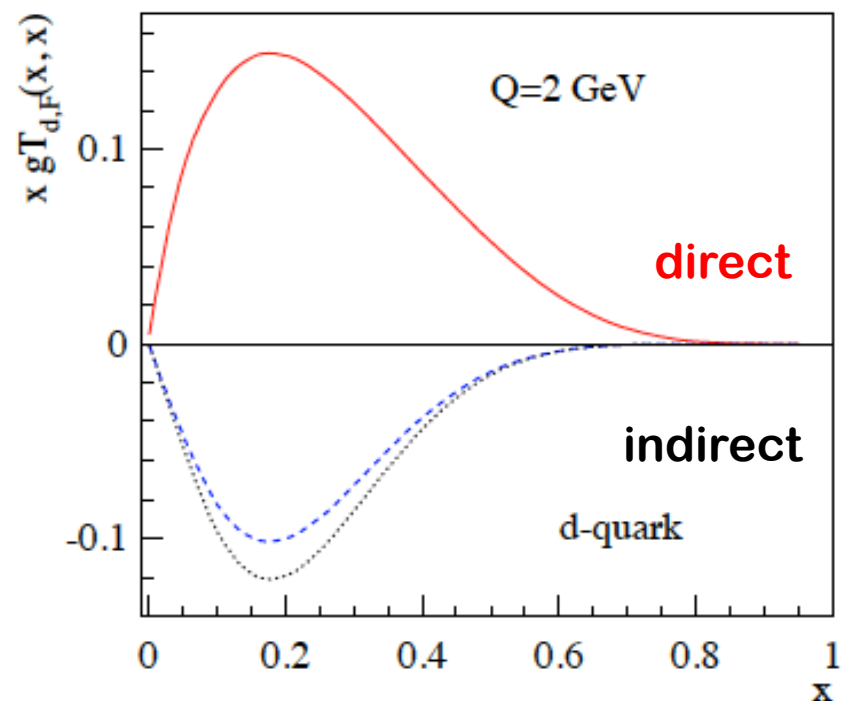
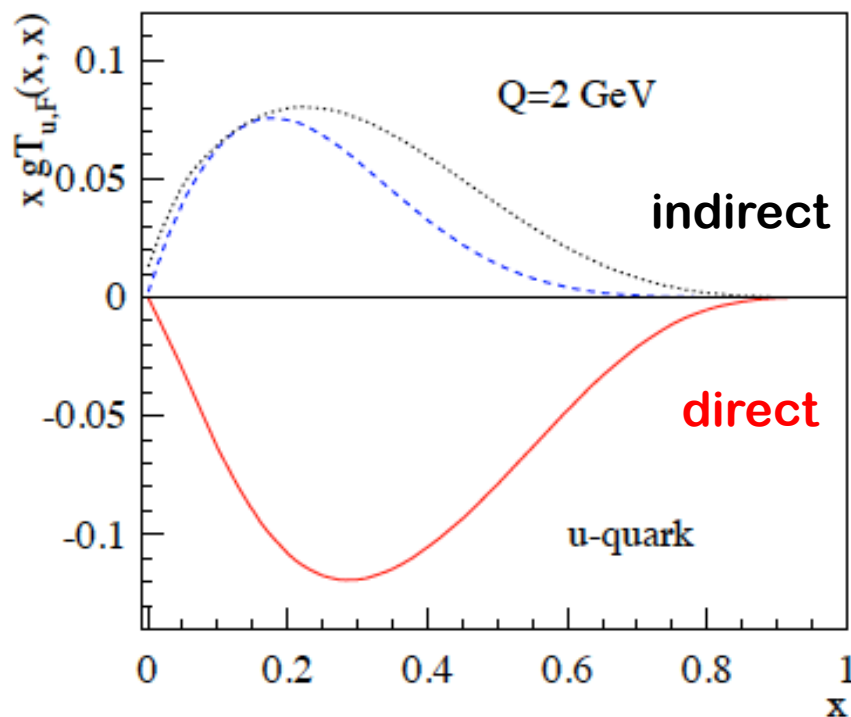
Kang, Qiu, Vogelsang, Yuan, 2011

□ Siverson function and twist-3 correlation:

$$gT_{q,F}(x, x) = - \int d^2 k_{\perp} \frac{|k_{\perp}|^2}{M} f_{1T}^{\perp q}(x, k_{\perp}^2) |_{\text{SIDIS}} + \text{UVCT}$$

□ “direct” and “indirect” twist-3 correlation functions:

Calculate $T_{q,F}(x, x)$ by using the measured Siverson functions

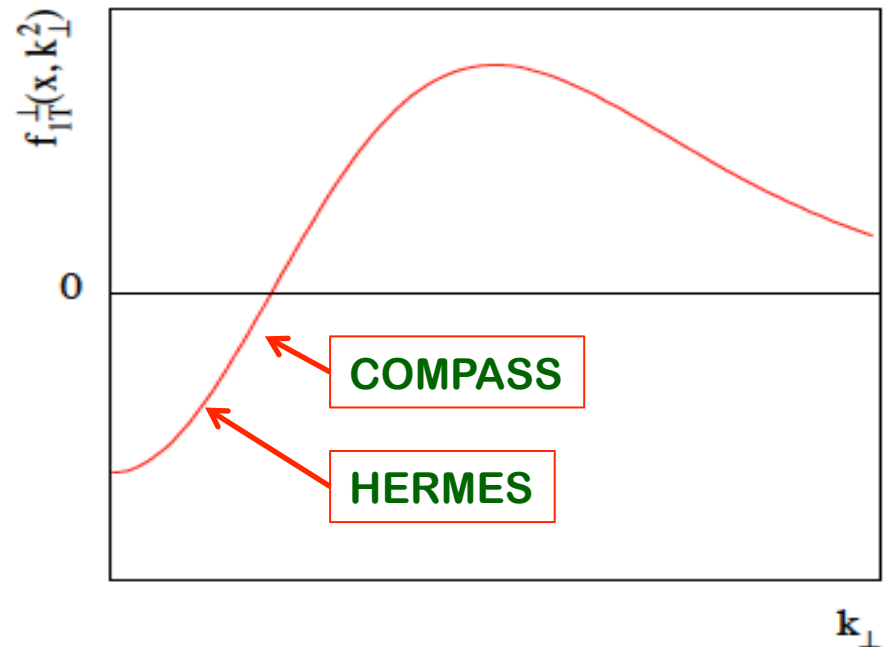


Possible interpretations

□ A node in k_T -distribution:

- ✧ Like the DSSV's $\Delta G(x)$
- ✧ HERMES vs COMPASS
- ✧ Physics behind the sign change

EIC can measure TMDs
for a wide range of k_T



□ Large twist-3 fragmentation contribution in RHIC data:

If Sivers-type initial-state effect is much smaller than fragmentation Effect and two effects have an opposite sign

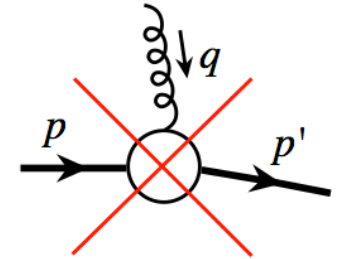
Can be tested by A_N of single jet or direct photon at RHIC

Parton's spatial distribution

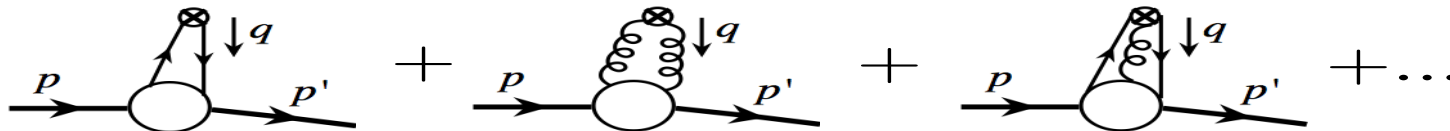
□ Form factor – spatial distribution:

Fourier transform of momentum transfer: $\Delta = p' - p$

But, no color form factor!



□ Need diffractive scattering:



But, every parton can participate – need a “localized” probe!

EIC at high energy can provide large Q , phase-space for Δ !

No natural large scale for hadronic diffractive scattering

No factorization for hadron-hadron diffractive scattering!

□ Questions/Tasks for theorists:

✧ 3D needs full range Δ , but, Factorization needs $Q \gg |\Delta|$?

✧ Contribution to the GPDs from multi-parton channels?

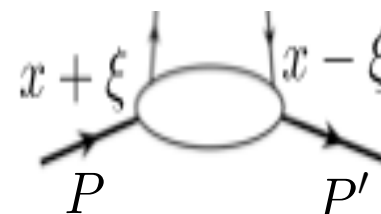
✧ ...

Generalized parton distributions (GPDs)

□ Quark GPDs:

$$\begin{aligned}
 F_q(x, \xi, t, \mu^2) &= \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P' | \bar{\psi}_q(\lambda/2) \frac{\gamma \cdot n}{2P \cdot n} \psi_q(-\lambda/2) | P \rangle \\
 &\equiv H_q(x, \xi, t, \mu^2) [\bar{U}(P') \gamma^\mu U(P)] \frac{n_\mu}{2P \cdot n} \\
 &\quad + E_q(x, \xi, t, \mu^2) \left[\bar{U}(P') \frac{i\sigma^{\mu\nu} (P' - P)_\nu}{2M} U(P) \right] \frac{n_\mu}{2P \cdot n}
 \end{aligned}$$

Muller, 94
Ji, 96, ...



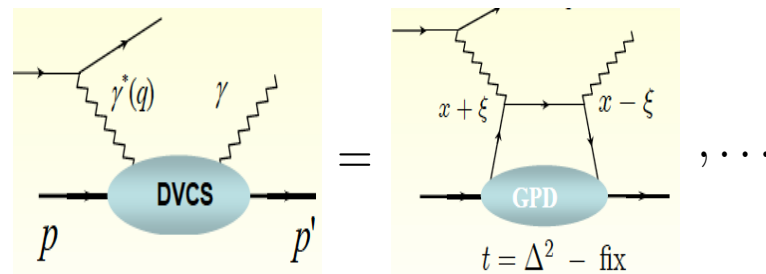
with $\xi = (P' - P) \cdot n/2$ and $t = (P' - P)^2 \Rightarrow -\Delta_\perp^2$ if $\xi \rightarrow 0$

Like PDFs, GPDs are not physical observables, scheme dependent!

□ Net parton's orbital motion:

Ji, PRL78, 1997

$$\begin{aligned}
 J_q &= \frac{1}{2} \lim_{t \rightarrow 0} \int dx x [H_q(x, \xi, t) + E_q(x, \xi, t)] \\
 &= \frac{1}{2} \Delta q + L_q
 \end{aligned}$$

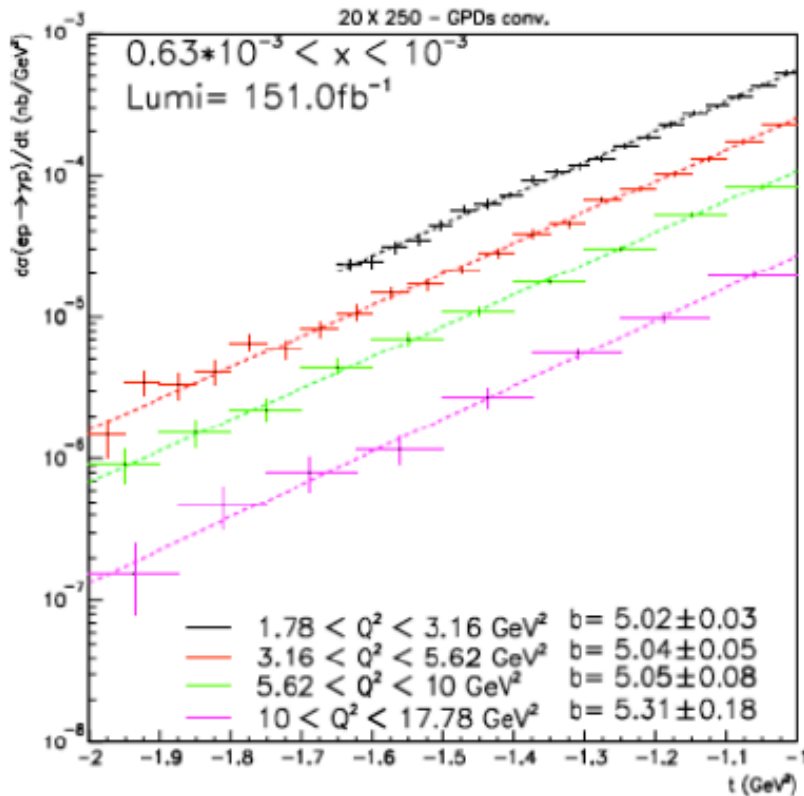


□ Connection to normal quark distribution:

$$H_q(x, 0, 0, \mu^2) = q(x, \mu^2)$$

DVCS at EIC

Simulated DVCS cross section
(150 fb⁻¹)



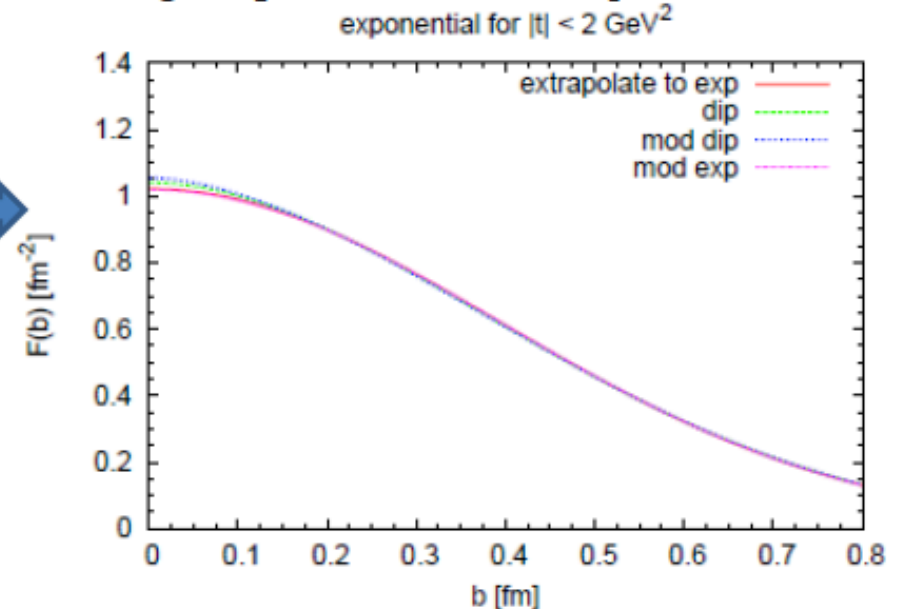
S. Fazio

- The slope of the t dependence can be extracted with 1% accuracy due to high luminosity!

(compare to ~10% accuracy at HERA)

- Extracted transverse distribution of “singlet quarks” down to $b_T \approx 0.05$ fm

F.T.



E. Aschenauer, M. Diehl, S. Fazio
(from the write-up of the INT10-03 program)

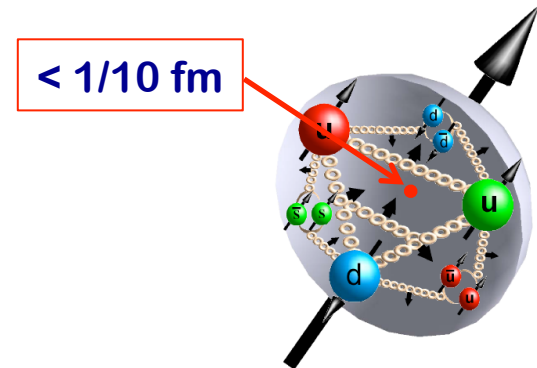
Guzey's talk at EICAC review

Summary

- ❑ QCD factorization/calculation have been very successful in interpreting HEP scattering data

- ❑ What about the hadron structure?

Not much!



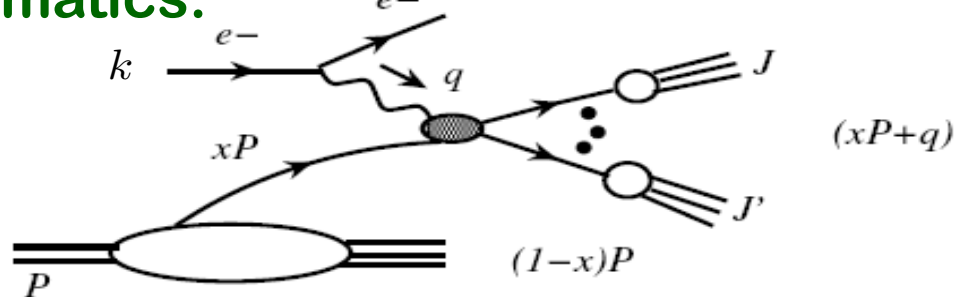
- ❑ EIC with a polarized hadron beam opens up many new ways to test QCD and to study hadron structure: TMDs, GPDs, ...
- ❑ The challenge for theorists is to indentify new, measurable, and factorizable observables that carry rich information on hadron's partonic structure

Thank you!

Backup slices

EIC Kinematics

DIS kinematics:



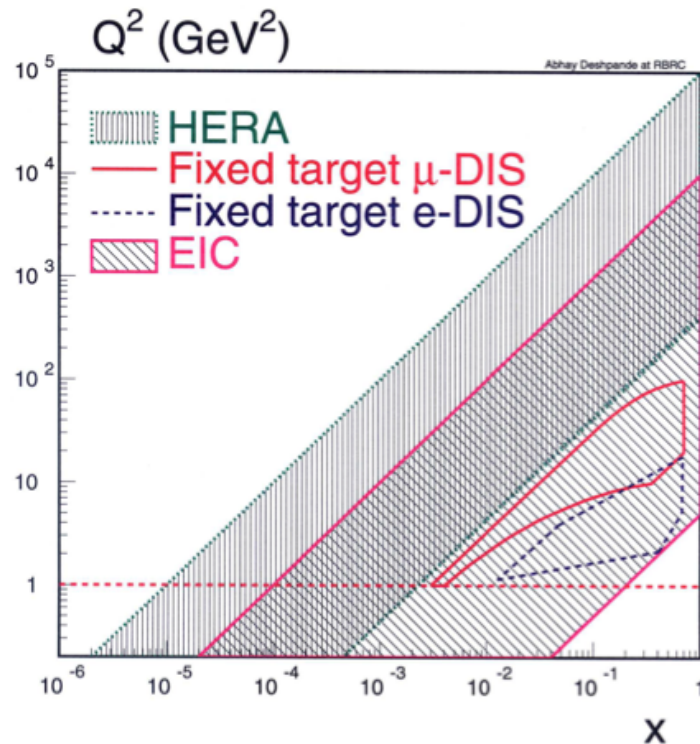
$$Q^2 = -q^2 = x_B y S$$

$$x_B = \frac{Q^2}{2p \cdot q}$$

$$y = \frac{p \cdot q}{p \cdot k}$$

$$S = (p + k)^2$$

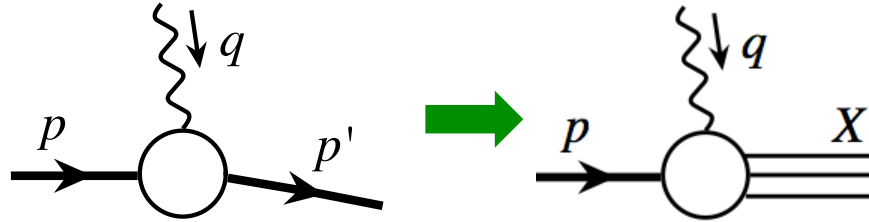
EIC (eRHIC – ELIC) basic parameters:



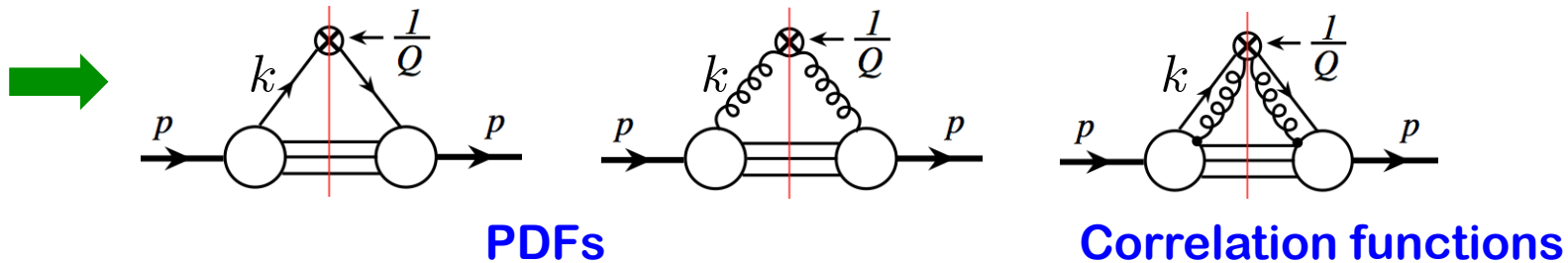
- ✧ $E_e = 10$ GeV (5-30 GeV available)
- ✧ $E_p = 250$ GeV (50-325 GeV available)
- ✧ $\sqrt{S} = 100$ GeV (30-200 GeV available)
- ✧ “localized” probe: $Q^2 \gtrsim 1$ GeV
- ✧ $x_{\min} \sim 10^{-4}$
- ✧ Luminosity $\sim 100 \times$ HERA
- ✧ Polarization, heavy ion beam, ...

EIC advantages

□ Inclusive DIS – Spin:



Forward scattering matrix elements:

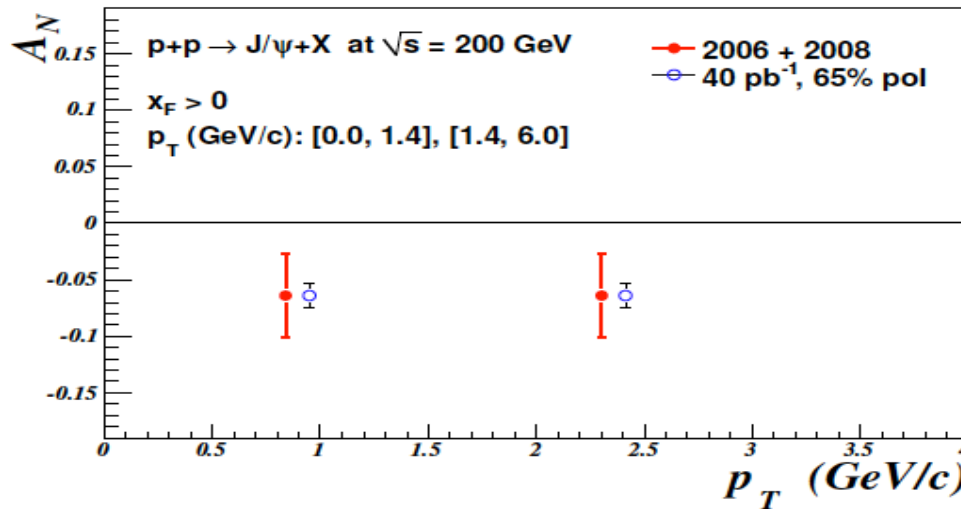


□ SIDIS – Best place to measure TMDs:

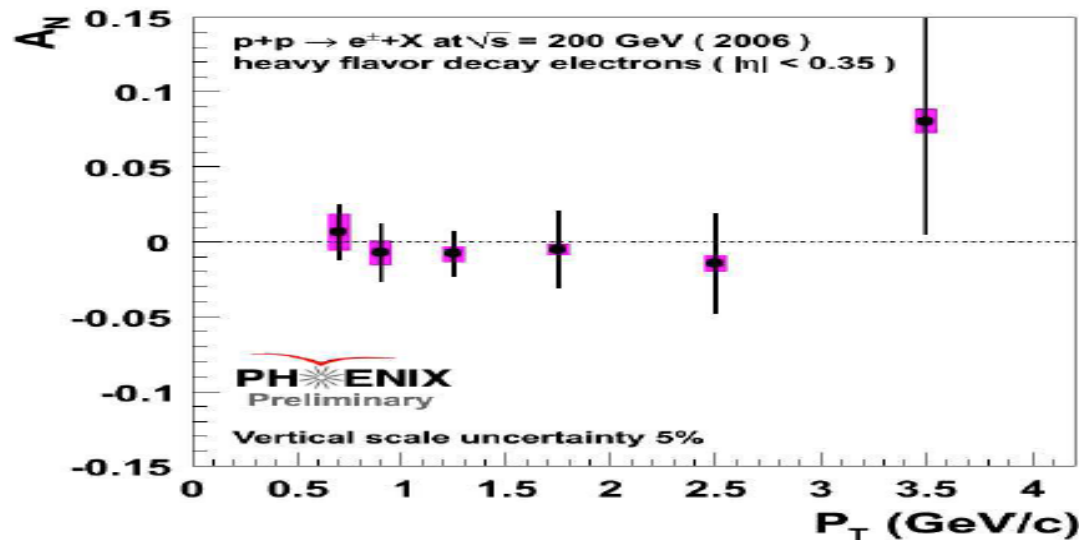
- ✧ TMD Factorization
- ✧ Naturally two very different scales: Q , p_T
- ✧ Well-defined lepton-plane and hadron-plane – separation of TMDs

First hint of tri-gluon correlation

□ PHENIX data on J/psi:



□ PHENIX data on open charm:



Collinear factorization:

- ✧ tri-gluon correlation
– direct quantum interference

Challenges:

- ✧ J/psi production mechanism
- ✧ Initial- vs final-state effect
- ✧ Connection to Gluon Sivers function

Collins, Qiu, Vogelsang,
Yuan, Rogers, Mulder, ...